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THIXOFORGING OF LOW CARBON STEEL SAE1006 BACKWARD THIXOEXTRUSION

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Abstract

For nearly two decades, researchers from academia and industry are working on the development of steel alloys thixoforging, which are not the easiest to form with this process. The early fundamental technology research demonstrated the feasibility for certain conditions. These works has focused on different steel grades, e.g. C38, M2…; different tools and their materials due to specific thermal and mechanical properties; better forming conditions; flow of the semisolid material; characteristics and the means of obtaining the semisolid state; evolution of the liquid fraction; mechanical models of deformation, process simulation, etc.

Today, it is necessary to continue the development by realizing technological demonstrators integrating some industrial constraints, like production rate and costs, but it is also necessary to identify and define the field of application of this process and its limits in terms of materials, tools, cadence, forming speed, etc. The major difficulties are the interactions and the coupling of these various parameters and conditions of this forming process making it difficult to understand the mechanisms of thixoforging.

In this context, a new steel grade was tested and studied. This SAE 1006 grade is deemed difficult to thixo-forge, due to its high melting point. The selected part geometries are not feasible with conventional forging. The present study reports the first results of the thixoforging of this steel for a product with specific geometric conditions and the means used and developed.

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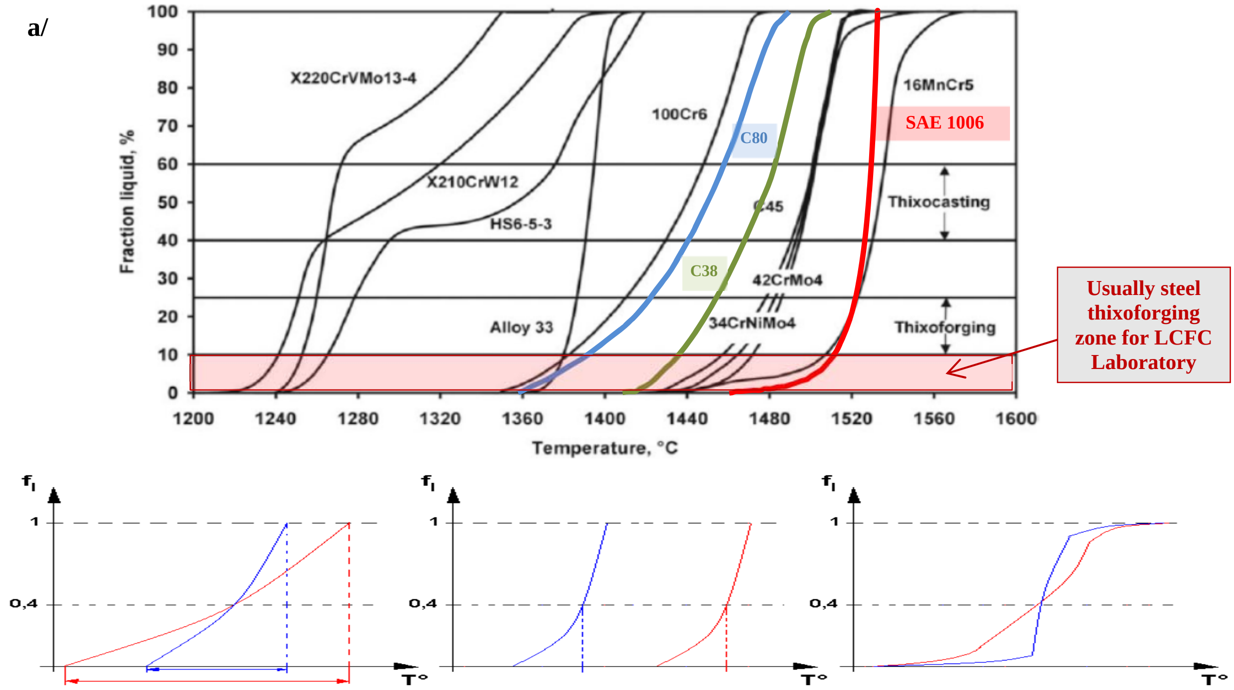
1. Introduction and context

The thixoforging of steels should allow in the medium term to offer a shaping solution associated with a specific design approach of the products to meet the increasing constraints of lightening of the parts in order to limit the carbon footprint. As a reminder [6][11], metal forming in the semisolid state makes it possible to produce parts with more complex shapes than conventional forging, often in a single forging step, with less material engaged which is in line with the evolution and current manufacture demand of new products meeting environmental standards. Unfortunately for the time being, industrial semisolid alloy forming is limited to alloys with low melting points, aluminum and magnesium. Even experimentally, the studies were limited to a small number of grades of steel as illustrated in Table 1.

Table 1. Different steel grades studies for thixoforging

Steel Grade	**SAE1006** Present work	**HP9/4/30** [13]	**C38** [2][14]	**C80** [5]	**M2** [7][10][12]
Carbon Percentage	0.05	0.30	0.38	0.80	0.85
Fusion temperature start	1456	1430	1430	1360	1230
Semi-Solid temperature range	63	60	100	125	225

The difficulties of steels thixoforging reside in high melting temperatures (see Table 1 and figure 1a and 1c), and in restricted windows for obtaining a billet with the optimal semisolid state for the shaping according to steel grade[8]. The accuracy of the billet temperature has a strong influence on the semisolid state (figure 1b), as well as the sometimes non-linear evolution of the liquid fraction as a function of temperature (figure 1d).



b / Width of the Semi-Solid temperature domain

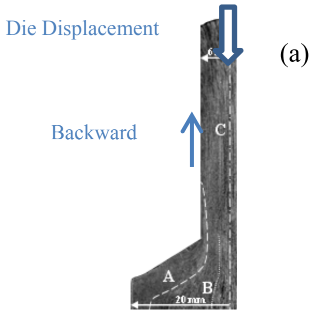
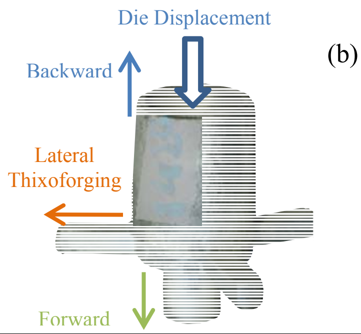
c / Average temperature of the Semi-Solid domain

d / Discontinuity or evolution of the liquid fraction

Fig. 1. (a) Liquid fractions for different steels as a function of temperature [4], completed with C80, C38 and SAE1006 Steels ; (b) (c) (d) Parameters defining a semisolid area for thixoforging.

Figure 1 (a) and Table 1 illustrate well these constraints of temperature control and its grade dependency. Table 1 clearly shows the influence of the carbon percentage, hence that of the alloy grade, on the lower melting temperature for a higher carbon quantity and larger temperature range between the start and the end of melting. Figure 1 (a) and Table 1 show that the low carbon steel SAE1006 has a very high melting temperature and a very low semisolid state temperature range 65 ° C. Under these conditions, the control of the semisolid state of the billet before shaping is very challenging.

Table 2. Examples of steel thixoforged parts from LCFC

	Backward thixoextrusion (half part) [1][2]	Multi direction thixoforging [3]
		
Principal goal(s)	Key parameters identification of the thixoforging process	Key characteristics for a viable application to high frequency industrialization of thixoforged parts

The present challenge is to define the application field of thixoforging, it is the aim of this research work using a steel never thixoforged until now and deemed difficult to thixoforge due to the conditions of obtaining the semisolid state. Moreover, the thixoforged part was obtained by backward thixoextrusion, which is a process controlled by the LCFC, table 2, and must make it possible to analyse quite simply the material, unlike the illustration of thixoforging (b), and associated microstructures. The selected part shape is a tube with specific dimensions that are difficult to obtain in conventional forging without severe tool wear, 6 mm thick walls over a height greater than 50 mm, figure 3. So with these choses, the range and new limits of the thixoforging of such parts in steel are evaluate

2. Experiments

The experiment consists in shaping a tube by backward thixoextrusion as illustrated in figure 2.

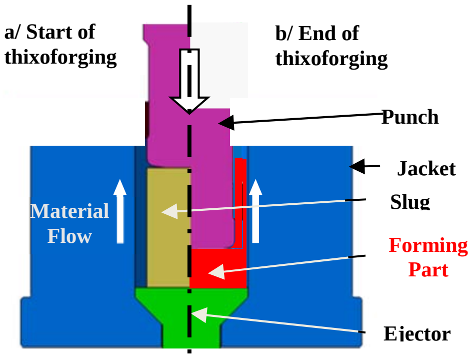


Fig. 2. Illustration of tube shaping by backward thixoextrusion (a) start of thixoforging; (b) End of thixoforging.

2.1. Material

The SAE1006 steel has a mass percentage of carbon of 0.053% (Table 3). As mentioned above, the study of SAE1006 steel must make it possible to define whether a low-carbon steel can be shaped by thixoforging because one of the main difficulties lies in obtaining a precise temperature, obtained rapidly and sufficiently repeatable corresponding to a semisolid state of this specific steel grade.

Table 3. Chemical composition of commercial SAE1006 low carbon steel used in experiments, mass%

C	Mn	P	S	Si	Al	N	Ni	Cr	Cu
0.053	…	0.022	0.008	0.184	-	-	-	0.06	-

In the case of the experiments presented, the mean temperature of the slugs was between 1465 °C and 1500 °C, with a pilot temperature set at 1480 °C. The raw slug dimensions before heating are 60 mm high and 45 mm in diameter obtained from a rolled bar. The steel has not undergone any treatment allowing obtaining an optimized microstructure for thixoforging, of type globular microstructure.

2.2. Process means

The SAE1006 steel billet undergoes 3 steps in the thixoforging process; the heating, the transfer, the forming.

To heat the slug, a low-frequency induction heater was used. The CELES-MP75 induction furnace characteristics are a maximum power of 75kW and a frequency of 1400Hz. It must be able to heat the slug by ensuring:

- the heating times, close to the industrial rates, that is to say less than 180 s,
- a sufficiently solid skin to allow manipulation during transfer [9]
- A semisolid slug inside that is as homogeneous temperature as possible [9]

The slug is shaped using X38CrMoV5 steel tools and a screw press capable of delivering 31.5 kJ at a maximum speed of 680 mm/s.

3. Thixoforging results

After the development of the experimental tests, 24 SAE1006 steel tubes were obtained by backward thixoextrusion. All of these elements meet the quality requirements set in terms of geometric and microstructural characteristics.

The measured thixoforming force at 1400 °C was 670 kN. This effort is 24% less compared to the conventional forging at 1250 °C, estimated at 900 kN by numerical simulation on Forge®. This reduction of forming effort can respond to the need to reduce the energy impact on the products manufacturing.

Figure 3 shows the dimensional and geometrical characteristics of the produced parts. The outer diameters of 57 mm and the inner diameter of 45 mm, measured at the height of 25 mm of the inner bottom, were more particularly checked, as well as the internal cylinder clearance angle of 0.5°.

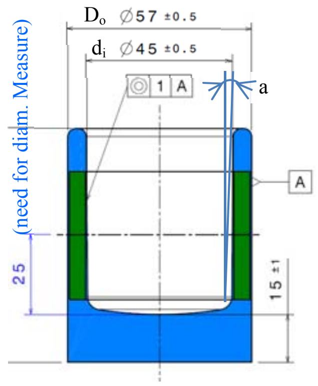


Fig. 3. Dimensional and geometric tolerances of the thixoforged tube.

The results of these measurements, of the 24 thixoforged tubes, are summarized in table 3.

Table 3. Measured dimensions of thixoforged tubes

	nominal	average	max	min	variability
D_o: outside diameter =57mm	57mm	56.83	56.91	56.78	0.13
a: clearance angle =0.5°	1°	1.11	1.21	1.01	0.2
d_i: inside diameter =45mm	45mm	44.19	44.31	44.14	0.17

All SAE1006 thixo-extruded steel parts meet all expected geometric and dimensional specifications. The differences between the maximums and the minimums of the different measurements are always lower than the tolerances set according to the conventional forging specifications.

Table 4 shows a micrograph of the SAE1006 steel before thixoforging sampled in the rolled bar and a macrograph of the thixoforged tube and a representative micrograph of the microstructure after thixoforging and cooling of the part in the open air.

Table 4. Micrographs before and after thixoforging and macrograph.

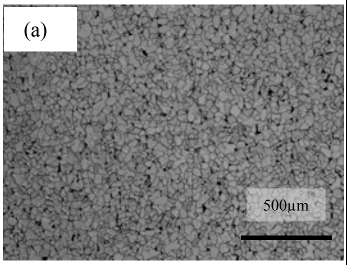
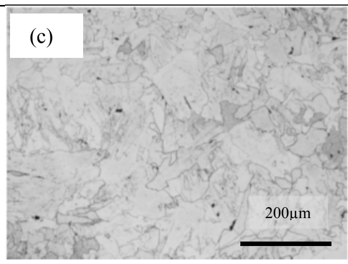
Microstructure of raw SAE1006	After thixoforging Macrostructure	After thixoforging Microstructure	Characteristics
(a) 	(b) 	(c) 	Tightened Gaussian distribution Grains of rounded shapes ASTM 6 [45-38] µm max 200 µm

Table 4 (c) shows a micrograph of the thixoforged cylinder with the corresponding grain size distributions. The microstructure is ferritic and the shape of the grains remains identical in the whole cylinder. The grains are rather elongated and of random and abrupt shapes. The grains size slightly varies along the height of the cylinder and their distribution shows a Gaussian behaviour. The microstructure remains globally homogeneous in the useful part of the cylinder as well as in the base, with an average grain size around 40 microns. The initial alloy microstructure (before the thixoforging step, Table 4 (a)) is different with equiaxed grains and a homogeneous size distribution centred around 40 microns.

The fiberizing of thixoforging part (Table 4 (b)) can be attributed to impurities segregation occurring during the hot deformation process. It can be noticed that this tendency of fiberizing is already observed in the alloy before the thixoforging step, resulting from the rod shaping.

4. Conclusion

The forming by backward thixoextrusion from low carbon steel SAE1006 is possible. The control of the conditions to obtain the steel semisolid state represents a difficulty, but the results on the parts are quite satisfactory from a macro and microscopic point of view, and they make it possible to envisage to thixoforge other different geometries, more complex from a flow material point of view, to confirm these good results under other shaping conditions. This work shows that it is possible to use new steel grades for thixoforging and that the field of its employability still needs to be explored and consolidated in order to propose new shaping solutions.

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